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MECHANICS OF FORMATION OF ARCUATE MOUNTAINS

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PART III

THE FOLDING PROCESS STUDIED IN THE PROFILE—FORMATION OF SLIDES

Imperfect plasticity of folding strata.—Thus far we have discussed the flexures in rocks as though the plasticity of folding sediments were sufficient in all cases to permit without failure the development of both underturned and recumbent anticlines. Such a condition appears to be realized in nature only in the case of well-laminated rock formations, and it is proper here to consider a little more fully the subject of plasticity within compressed sediments under load and at somewhat elevated temperature.

At the surface of the earth so-called "hard rocks" behave like highly elastic bodies, and the degree to which this property of elasticity is modified by load has prevented a simple mathematical discussion of the subject of folding. Rudzki has stated perhaps as clearly as anyone the reciprocal relations of the properties of elasticity and plasticity in solid bodies.

> The elastic force with which the body resists the deforming force diminishes with time. The time which is necessary for the resisting force to fall to $\frac{1}{e}$ of its original value is called after Maxwell the relaxation time. A body is so much the more plastic the smaller the relaxation time. According to the

kinetic theory one may assume that all bodies are plastic to a certain degree, and that the differences have quantitative value. Obviously for room temperature and atmospheric pressure different bodies possess very different relaxation times. For steel the relaxation time may be some centuries; for wax, paraffine, etc., it is so small that the determination of the elastic constants by the usual static methods is difficult to carry out. Plasticity appears in some cases to be dependent upon the magnitude of the deforming force—it is larger and the relaxation time smaller the greater the force. Temperature has the greatest influence upon plasticity, the plasticity increasing with the temperature. Glass, which is at ordinary temperatures so brittle and breakable, shows distinct plasticity above 300° C. (order of magnitude of the relaxation time about a day).[1]

Quite obviously, where not centuries only but very much larger units of time may be involved in the folding process, the load which is necessary to produce plasticity sufficient for folding may be very much less than that indicated by experiments.[2]

There is, however, a way of looking at the subject of potential plasticity as it relates to folding strata, which will give us an insight into the conditions under which failure may occur. The different parts of a fold are subject to internal strains which in the anticlines of relatively late stage differ by large amounts. It therefore occurs that the period covered by the evolution of a fold may be sufficiently long to permit the resisting forces within the strata to fall, and local strains to occur without failure except at critical points of maximum deformation. In this event failure will occur at the locus of maximum deformation much as it would in a relatively elastic body, even though the remaining portion of the arch adjusts itself to the stress conditions like a truly plastic body. Our problem is, therefore, to discover the locus of maximum strain in a growing anticline.

Contrasted cases of isotropic and anisotropic strata—control of internal strains by lamination.—The problem of representing the system of internal strains within a developing anticline is complicated by the variations in texture which characterize rock formations. There are, on the one hand, formations such as heavy limestone or dolomite members which are largely devoid of lamination planes and hence to be regarded as not only nearly homogeneous but approximately isotropic as well. Rather generally, however, sediments are characterized by more or less numerous planes of ready separation (lamination) parallel to the original upper and lower surfaces of the formation, and such formations are to be regarded as essentially anisotropic with a minimum of cohesion at right angles to the lamination planes. The movements of particles due to internal stresses are of necessity guided by these surfaces, since the adjacent thin layers permit of the differential sliding (shearing) motions generally described as accommodation between layers. The more perfect the lamination, the more readily does the stratum rise to form an arch. On the contrary, any tendency toward cross-fractures in the strata, such as are generally to be found in shales, lowers the strength of the arch and brings about its failure. The significance of lamination in this connection may be the better appreciated by considering the bending of two rods, one of wood cut parallel to the grain, and the other shaped from some isotropic substance like glass or wax. The rod cut parallel to the grain possesses large cohesion in the direction necessary to resist strong tension upon the convex surface when bent, but the least cohesion in the direction to facilitate the necessary adjustment by shearing between parallel longitudinal layers within the mass.

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[1] *Physik der Erde* (author's German translation), Leipzig, 1911, pp. 232–33.

[2] See in this connection, F. D. Adams, "An Experimental Contribution to the Question of the Depth of the Zone of Flow in the Earth's Crust," *Jour. Geol.*, XX (1912), 97–118; L. V. King, "On the Limiting Strength of Rocks under Conditions of Stress Existing in the Earth's Interior," *ibid.*, pp. 119–38.

Shearing movements within an anticline for the contrasted cases of isotropic and of well-laminated strata.—For the case of laminated strata we may study the internal strains within an anticline by means of a simple experiment. Two exactly similar piles of paper were taken, each some two feet or more in length, two inches in width, and one inch in thickness. Upon the long edges of these piles series of tangent circles were carefully drawn in ink, each with its vertical diameter. The circle was chosen as guide form, both because it is the figure of highest symmetry and favors no one direction more than another, and because conglomerate pebbles, by rudely simulating in some cases this form in section, have sometimes preserved a valuable record of deformations within anticlinal arches.

Thus prepared, one of the piles was bent into the form of an unsymmetrical anticline (Fig. 30), the other being preserved as it was for purposes of comparison and to note the measure of crustal shortening in anticline evolution. Observing now the deformations

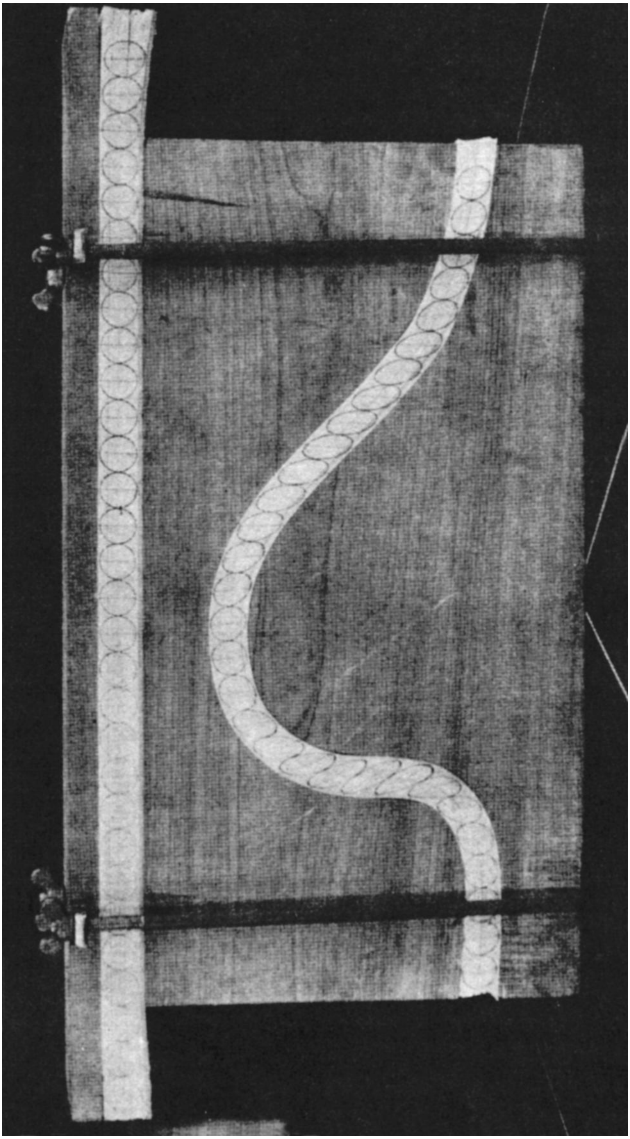

FIG. 30.—Model to illustrate the internal strains which are developed within a stratum in the process of folding

of the guide circles, it is found that slight deformation only has occurred in the neighborhood of the crest of the anticline and near the trough of the neighboring syncline (a slight elongation of the vertical diameter). Elsewhere at all points on either side of the points of inflection of the fold a more complex deformation has taken place, for the circles have been transformed into more or less elongated obovate figures with the greatest elongation at the

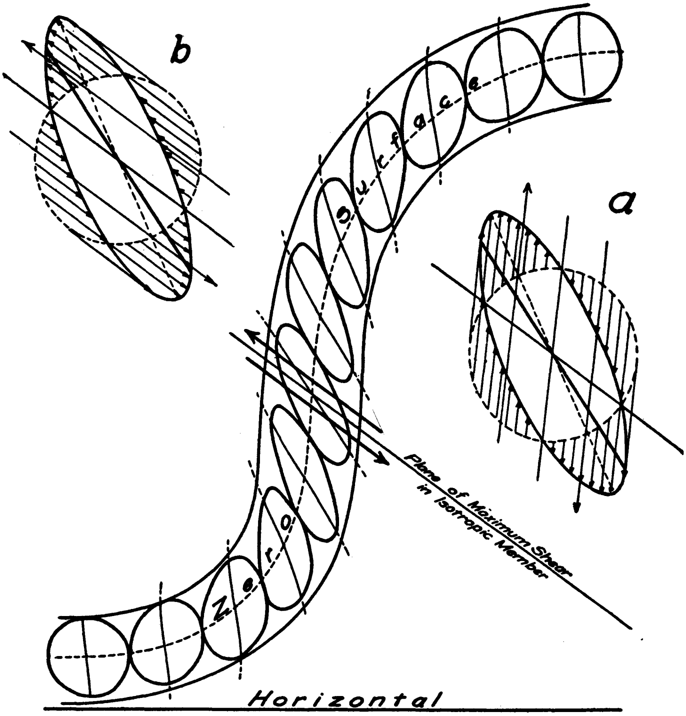

FIG. 31.—Steeper limb of the anticline produced from a pile of paper to show the deformed guide circles (traced): *a*, enlarged diagram at the point of inflection to show the actual migrations of particles by shearing movements parallel to the lamination; *b*, enlarged diagram of the deformations at the point of inflection if the stratum bent had been from isotropic material.

points of inflection. Comparing the upper and flatter with the lower and steeper limb of the anticline, we find that deformation has been greater in the steeper limb, and since we are seeking the locus of maximum deformation we will examine this limb somewhat more in detail (Fig. 31).

Above the point of inflection of the limb it is to be noted that the originally vertical diameters of the guide circles now diverge upward, thus indicating that there has been tension upon the convex side and compression upon the concave side of the stratum. These relations are reversed in the synclinal portion. The points of inflection of the double curves into which the guide circle diameters have been transformed define a surface within the stratum which has been neither expanded nor contracted and is known as the "zero surface." This surface is in the true anticline section below, and in the syncline section above the median surface of the stratum.[1]

Earlier failure in anticlines of unlaminated or poorly laminated strata.—At the point of inflection in the steeper anticline limb, deformation is clearly at a maximum, and failure, if it is to occur, will be located here. The enlarged diagrams *a* and *b* of Fig. 31, which set forth the original and the deformed conditions of the guide circles at this critical point, show that there are two exactly similar common diameters to the circle and ellipse and that the observed deformations might have taken place through migrations of individual particles either in one or in the other of two ways, dependent upon which offered the minimum of resistance. Obviously the slight cohesion to be overcome by the shear of the paper laminae over each other has determined that in the case of our experiment—a well-laminated (anisotropic) stratum—adjustments shall take place parallel to the laminae, for which reason failure is little likely to result until a late stage of the anticline has been evolved. Had our stratum been, on the other hand, without lamination planes (isotropic), adjustments would have taken place in the sense of diagram *b*, and failure would have occurred parallel to the other common diameter in the figure as an application of the principle of greater weakness on the section of minimum area.

As an application of these considerations we find that unlaminated strong members like limestone fail in the process of anticline formation at an early stage and near the point of inflection of the lower limb; whereas anticlines in tough laminated strata persist until strongly underturned and then fail only after excessive stretching of the under limb and at an angle with the base which would indicate that the adjustments of individual particles were nearly or quite parallel to the laminae. These contrasted examples illustrate respectively Willis' types of "break thrusts" and "stretch thrusts"[1] (Fig. 32).

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[1] When well-laminated rock formations lie beneath a competent member of heavy massive rock like limestone, the strong tendency to shear along lamination surfaces may result in a complicated puckering of the laminated inferior formation even though the arch in the competent formation remains comparatively simple. This phenomenon so often observed in folded mountain regions and reproduced by Willis in his experiments (*The Mechanics of Appalachian Structure*, Pl. 90) involves an attenuation of the puckered laminae. It is also to be observed that the puckerings or plications are concentrated in the crown of the anticline where tension in the stratum protected may supply the space necessary for duplication by plication.

The second arch within a series of anticlines may in its turn fail in a manner similar to the first, and others of the series in succession; thus yielding a series of slices which in early stages at least dip away from the active force of compression and are described as "imbricated structure" (*Schuppenstruktur*, Fig. 25, *B*).

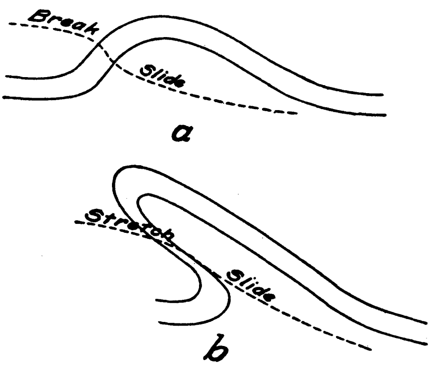

FIG. 32.—Diagrams to illustrate failure in anticlines; *a*, in an isotropic member such as limestone—break slide, or "break thrust"; *b*, in a tough laminated member such as schist—stretch slide, or "stretch thrust."

Slides and their modified direction after leaving the competent member.—The names in most general use, or at least in longest use, for the surface of failure within an anticline are "thrust" and "overthrust." The former is in every way undesirable because so likely to be confused with the same term in general use in mechanics for an active force; while the latter term is further objectionable in that it assumes that the active force responsible for the surface of failure operated from above and behind the anticline. Suess's term "sole" (*Sohle*), now employed by many, is without these objections, but the word "slide" recently suggested by Bailey[2] is perhaps even better.

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[1] Willis, *op. cit.*, p. 223.

[2] E. B. Bailey, "Recumbent Folds in the Schists of the Scottish Highlands," *Quart. Jour. Geol. Soc.*, LXVI (1910), 593.

With the advent of failure in an anticline a new resolution of the active force of compression takes place with components parallel and perpendicular to the slide, movement is facilitated, and the potential energy of the system of stresses falls in consequence. The acute angle which the active force makes with the slide, and the reduced resistance opposed to shear along that surface, alike favor the underthrusting of the lower portion of the severed limb of the anticline beneath the upper (Fig. 25, *A*).

In the case of a well-laminated formation where a "stretch slide" has occurred, the slide, being nearly or quite parallel to the lamination, is extended along the lamination planes on either side within the inferior and superior formations of the series. Since the anticline contains the most steeply inclined of the layers, the dip of the slide is progressively flattened as it passes out from the anticline in either direction. For the case of a "break slide" within massive sediments, the entry into these surfaces of least resistance to slide may be less easily made but in either case a local swell of the slide surface may result. Both the low dip angles and the undulations of slides are well established by observation in many districts. The entry of the slides into the bedding planes of the formations tends to make of the severed rock formations a series of flatly disposed and widely extended slices capable of individual lateral migrations in mass, which in view of their position relative to the active force should be described as "underthrusting."

Underthrusting of rock slices separated by slides simulated in experiment.—If we represent the relatively thin slices, which are separated by slides dipping at low angles away from the active force, by a series of overlapping cards resting upon a stretched rubber sheet, and the unfolded neighboring sections on either hand by similar cards laid end to end as essentially continuous and hence relatively rigid sections of strata (Fig. 33), we may illustrate the underthrusting of the strata if we allow the rubber sheet to contract through releasing the tension upon it. With excessive underthrusting the cards are piled into a low dome elevated by the underdriving of the cards in proportion as the contraction of the rubber sheet has been large. It may happen also that the cards above and at the front dip forward and overlap at the forward end those lower in the series. This latter feature is a well-known peculiarity of the *Deckenbau* upon the northern border of the Alps (Fig. 34), and it is clearly favored by the sinking crowns of recumbent anticlines.

Formation of drag folds and listric surfaces at the front of underthrust slices.—The new system of stresses, which is inaugurated with the process of underthrusting, may lead to the formation of secondary folds and eventually to secondary slides within the mass beneath which a slice is driven. This driving-in of one slice after another not only produces friction breccia ("mylonite") at the contacts, but pushes upward and tends to fold under the frontal portion particularly of each underdriven slice. The active force of compression being still directed from in front of the folds and below, the "drag folds" which result (Figs. 34 and 35) should be underturned from the front, attenuated in the underturned lower limb, and eventually underthrust in that limb, much as are the folds of larger order of magnitude upon whose fractured remnants they have been superimposed. Instead, however, of being extended for any long distance on bedding planes, these secondary slides should here converge into the subjacent major slide. The shovel-like curvature which is so generally characteristic of them has suggested the name "listric surfaces" applied to them by Suess[1] (Fig. 35, Rigihochfluh and Mythen, and Fig. 37).

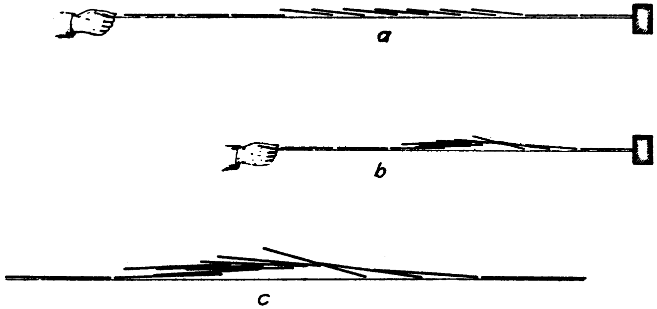

FIG. 33.—Diagram illustrating underthrusting of slices

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[1] *Listrische Flächen* (*Das Antlitz der Erde,* III, Pt. II, p. 612; *The Face of the Earth,* IV, 536).

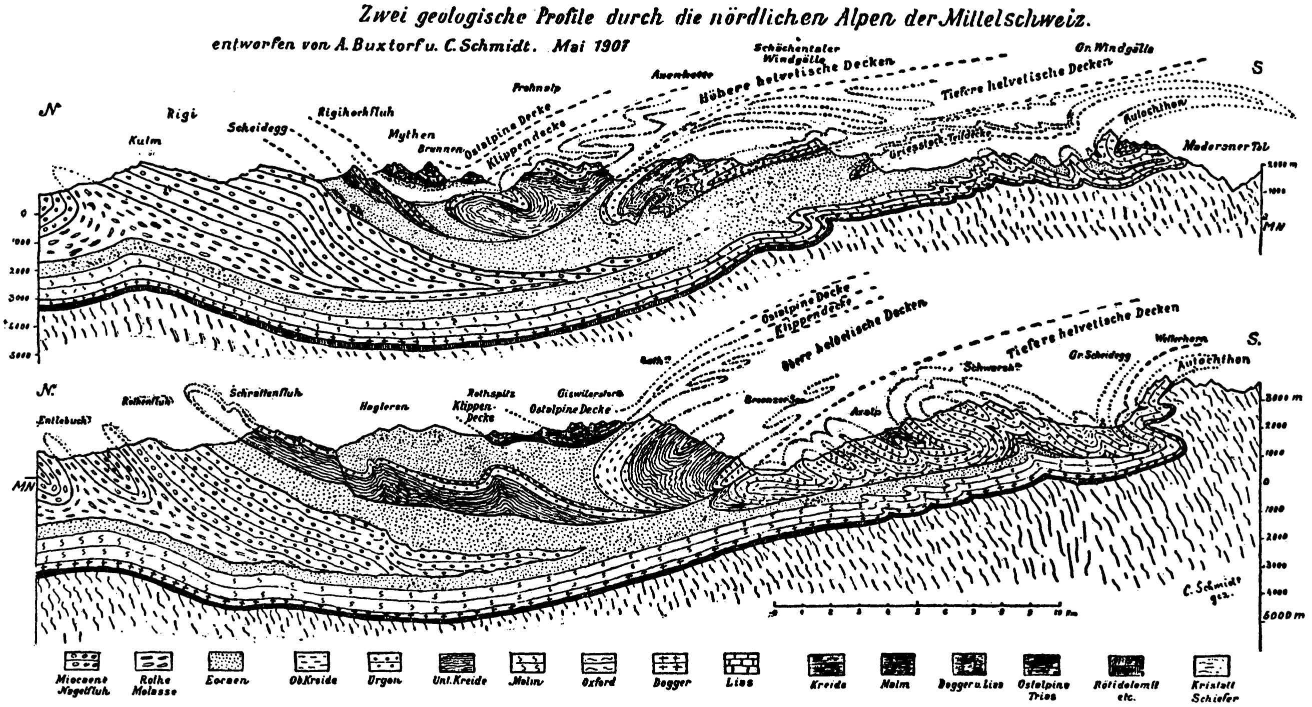

FIG. 34.—Two geological profiles through the northern Alps in middle Switzerland which show the characteristic frontal overlapping of slices and the formation of drag folds and listric surfaces (after Buxtorf and Schmidt).

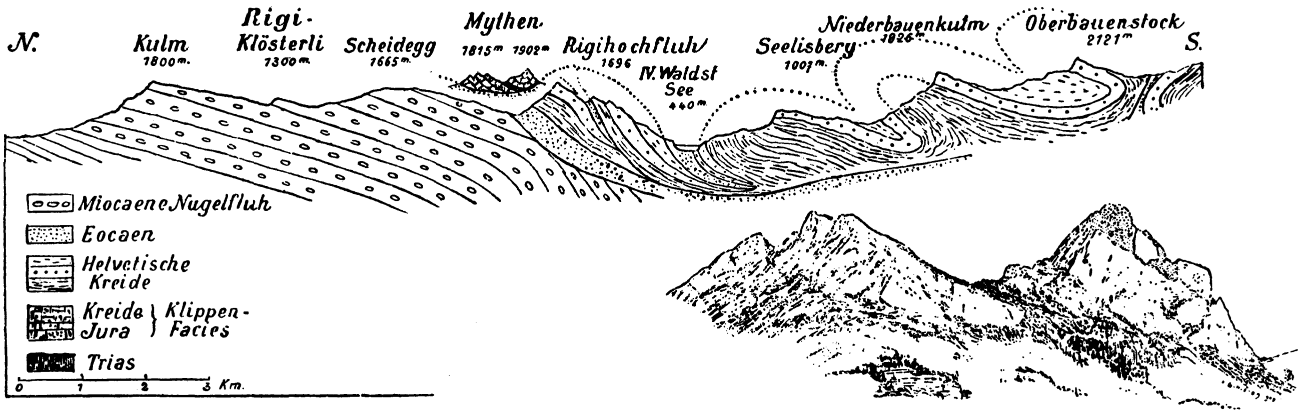

FIG. 35.—Profile of the front of one of the slides in the northern Alps to bring out the relationship of major slides to listric surfaces. At the right a sketch of the Mythen (after Tobler, Buxtorf, and C. Schmidt).

The relationship to each other in position of the listric surfaces which are produced by drag suggests the peculiar shearing surfaces which are seen at the snouts of some glaciers, save only that the distribution of forces is essentially reciprocal. It is the *upper* layers of the glacier which are pushed *forward* and *override* the lower layers held back by friction (Fig. 36). As a consequence, and as already pointed out (*ante*, p. 181), it is the upper limb of each fold rather than the lower that here becomes attenuated.

Extended slides within folded strata of mountains would appear to be greatly favored by the presence of a weak formation immediately above the competent member, this weak formation acting, so to speak, as a lubricant for the slide surface. It is no doubt significant that in the Alps the weak Flysch overlies the Helvetian limestones, for this yielding formation underlies one great slide after another in the series —"*Wildflysch*" (Figs. 34 and 35). It may also be of significance that within the same region the formation against which the slides rise at the front with the greatest development of listric surfaces is the hard *Nagelfluh* conglomerate, which has a local development only upon the northern margin of the Alps, and opposite whose areas rise the largest accumulation of rock slices.

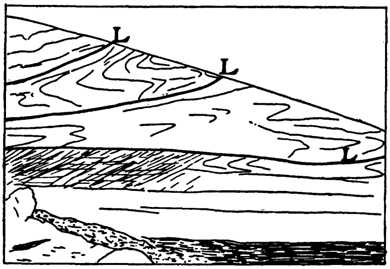

FIG. 36.—Slide surfaces in a glacier snout (after T. C. Chamberlin).

Examination of numerous profiles which include rock slides indicate pretty clearly that portions of the indriven slices have sometimes become involved in the complex of wedges at the front of each overlying slice (Fig. 37). Sections of the Belgian coalfield (Fig. 37, *e* and *f*) and of Buffalo Mountain[1] (Fig. 38) may be cited as examples.

SUMMARY

The Alps represent the type of Asiatic mountain arcs, and hence in explaining their tectonics deductions from Asiatic studies are to be utilized. Arcuate structure representing a reduplication of strata in recumbent and ruptured folds requires that the duplicated material shall have migrated centripetally from outside the arc and implies that the mass within is relatively the more rigid.

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[1] Arthur Keith, "Roan Mountain Folio, Tennessee–North Carolina," *Folio 151, U.S. Geol. Surv.*, 1907, p. 9.

The arcuate ranges of Asia, regarded not individually but as a system, favor the conclusion which we have reached of centripetally distributed thrusts directed toward the center of the system: (1) by their plan of arrangement; (2) by the position of the relatively rigid area (Angara Land); (3) by the greater geological age of the central, and the newer formation of the peripheral arcuate ranges; and (4) by the present locus of intense volcanic and seismic activity along the outer margin.

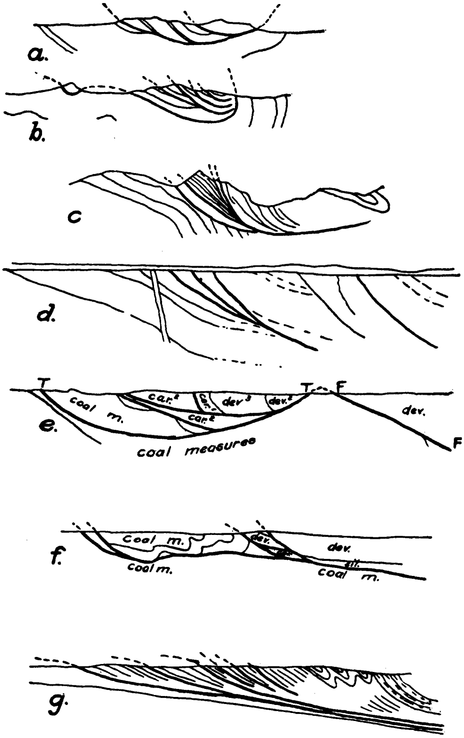

FIG. 37.—Examples of listric surfaces developed at the forward end of major slides: *a* and *b*, Buffalo Mountain, southern Appalachians (Keith); *c*, Rigihochfluh, northern Alps (Tobler and Buxtorf); *d*, Belgian coal-fields from St. Éloi to St. Léon (Briart as reproduced by Suess); *e*, Belgian coal-field at Fontaine-l'Évêque (Briart and Suess); *f*, the same near Denain and Anzin (Bertrand and Suess); *g*, North-central Carpathians (Uhlig). For better comparison all sections have been made to look north, northeast, or east.

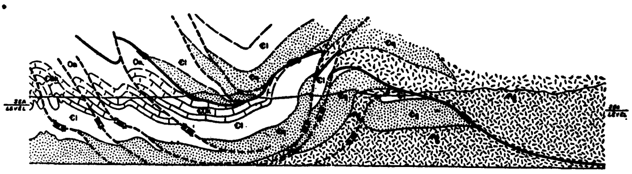

FIG. 38.—One of the sections through Roan Mountain in the southern Appalachians (after Keith).

The ocean floors are today for the most part sinking and represent the great areas of dispersal of thrusts toward the neighboring continents, and mountain arcs should therefore be convex toward oceanic depressions. If in the past during mountain-making periods ocean floors have represented areas of dispersal of thrusts, the position and the orientation of the earlier arcs should be an expression of the former areal relations of the continental pedestals and the ocean floors. For the continent of Asia this theory appears to be borne out by what we know of continental evolution within the principal mountain-making periods.

The active force (thrust) which produces rock folds, instead of operating from behind and above the anticline, as so generally supposed, is applied below and in front. Continuation of the process yields therefore not "overturned" and "overthrust," but *underturned* and *underthrust* flexures. Applied to the Alps, this requires that the main active force concerned in their folding came from the northwest, instead of the southeast, as generally assumed.

Anticlines arise first upon that side of the folding area which is toward the direction from which the force comes. In strong or competent members anticlines lift a portion of the load from arched underlying formations, and this portion, regarded as a percentage of the total load upon the arch, is at first small, but afterward rises steadily and rapidly up to the stage of underturning, after which it rapidly diminishes.

With the underturning of an anticline a new distribution of stresses is inaugurated, as a result of which a second anticline may develop behind the first and subsequently others in succession but of steadily diminishing dimensions until the series comes to an end. Thus it comes about that while the arcs in the order of their age develop from within outward in the series as the continental area becomes extended peripherally, the *folds (anticlines) within any arc* are developed in order of age from without inward (Fig. 39).

With the stage of underturning a new couple composed of vertical forces enters and tends to rotate the underturned arch, not forward as before, but downward; and if the competent member is overlaid by a weak formation, the crown of the arch will be left without sufficient support and will sink to form a "plunging crown." If supported by a strong formation this will not occur, but it will in any case eventually be rotated as a whole about its base and form a normal recumbent anticline.

Subsequent to the stage of underturning of the anticline, the active force of compression tends to reduce the volume of the included roll of the inferior strata with the effect of stretching and attenuating the under limb of the anticline in the competent member. Attenuated upper limbs of anticlines, though unknown in rock folds, are illustrated by the ice-folds within glacier snouts, where they are due to true overturning movements.

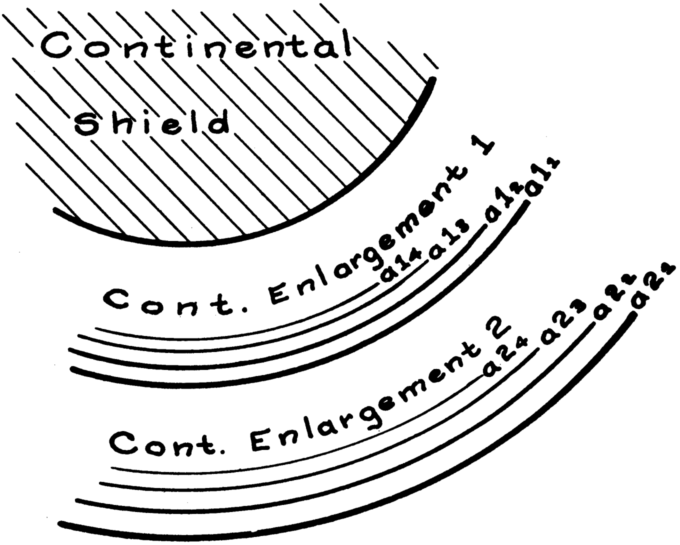

FIG. 39.—Schematic diagram to illustrate the order of development of mountain arcs from within the series outward, and the development of anticlines within each arc from without inward.

The partial relief of load from the inferior formations beneath the competent member in the arch may make possible under suitable conditions of temperature a local development of a magma macula; and the tendency to reduction of volume with continued underturning of the anticline supplies an efficient cause of the elevation of such lava toward the earth's surface. Association both in time and in place of volcanoes of the Pacific type with growing mountain arcs would thus be accounted for.

Backfolding occurs where relatively competent rock formations are locally replaced by weak material, or where a surface of disjunction transects the formation. The backfold develops in front of and eventually above the zone or surface of weakness.

The evolution of an anticline to late stages of underturning is directly determined by the measure of lamination of the competent member and the toughness of the laminae. Relatively strong rocks devoid of lamination fail by cross shear ("break slide") and at a much earlier stage of the anticline than tough well-laminated rocks which, on the contrary, fail on disjunctive surfaces which are nearly or quite parallel to the lamination ("stretch slide").

After failure of an anticline has occurred, a new resolution of the external forces takes place with components parallel and perpendicular respectively to the surface of failure (slide); this surface tends to be extended in either direction along surfaces of least resistance—usually bedding planes—and is thus flattened as it recedes from the competent arch. With the advent of the slides, migrations of the severed parts of the fold are greatly facilitated, and movements of the rock slices take place in such a sense that the lower are driven in beneath the upper—underthrusting.

The large friction on slides incident to underthrusting is reduced by a weak formation superior to the competent member. Friction breccia (mylonite) generally marks the position of the slide which develops special features at its forward end. Here are found secondary folds (drag folds) and secondary slides (listric surfaces), the former being underturned and attenuated in the underlimb, while the latter are concave upward (shovel-shaped) and converge into the major slide below. The lower of two contiguous slices may be ruptured and involved in the complex of curved wedges at the front of the slice immediately above.

September 15, 1913